# Monitoring and Control of a Flying Projectile and Ducted Fan

**Senior Design Proposal**
**Fall 2003**

**Submitted to Dr. B.C. Chang, Dr. Harry Kwatny, and the Senior Design Project Committee of the Mechanical Engineering Department at Drexel University**

**Team Number:**
**MEM-21**

**Team Members:**



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# Abstract

Unmanned aerial vehicles (UAVs) are a vital resource for military and civilian purposes that can be used for scouting and surveying of remote and inaccessible terrain, spying on enemy position, and security surveillance. The objective of this senior design project is to construct a small autonomous flying vehicle capable of real time position measurement with self-control. The UAV is composed of a ducted fan design powered by a lithium ion polymer battery and utilizes accelerometers, magnetometers, and various sensors for vehicle attitude measurement, position detection and obstacle avoidance. At the center of the vehicle, an Atmel AVR ATMega16 microcontroller will gather and process all the information from the sensors to maintain a constant stability of the system. Utilizing Mathematica version 4 and the dynamics package associated with ProPac version 3, the system dynamics will be modeled and verified. Based on this outcome, a controller will be written in an embedded C program that will be converted into an assembly language with Atmel AVR Studio. Finally, a prototype will be constructed and evaluated in real flight tests, with revisions made accordingly.

# Table of Contents

## I. Introduction:

### Problem Background:

The key to any military operation has always been exceptional intelligence. This includes, but is not limited to, enemy numbers, location, and composition. Until very recently, the United States Army had always used manned vehicles or personnel to get this information. However, in recent combat situations, including Afghanistan and Iraq, unmanned aerial vehicles (UAV) have played a much greater role. UAVs have the ability to gain as much, in some cases more, information without putting human lives at stake. However, their key drawback has always been their size. This severely limits their uses and makes them inaccessible to field personnel. The army has now shifted its focus towards smaller versions of aerial UAVs to help give field personnel an extra edge.

Two major design issues arise when working with smaller versions of UAVs. The first is the power required to launch and maintain a vehicle in flight. To minimize the power required, the vehicle must be as light as possible. It must also have a propulsion method which maximizes the amount of thrust vs. the power required to generate it. The second issue is the control of the vehicle once it is airborne. In order to properly measure the position of a vehicle, sensors such as accelerometers and magnetometers must be used. This sensor data must then be imported by a microcontroller capable of processing the information to adjust the position of the vehicle.

### Problem Statement:

The objective of this senior design project is to construct a small autonomous flying vehicle capable of real-time position measurement and self-control. To achieve this objective, a ducted fan design will be utilized along with a microcontroller for data processing. This aerial vehicle will be able to make fine adjustments in its trajectory and attitude based upon information received from onboard sensors.

### Constraints on the Solution:

The main constraint of the project is the size of the vehicle. As mentioned before, the smaller the size, the less thrust is necessary to maintain level flight. This will be of key importance, because it will enable the vehicle to stay in flight for a longer period of time by minimizing the power consumption, and increasing the payload capacity. Another constraint is the type of the sensors and microcontrollers used. With the environment being so chaotic (wind gusts, temperature changes, etc), the sensors and microcontroller must be able to communicate quickly and efficiently. The sensors must also be able to acquire real time data with high accuracy. Cost is the final constraint which arises. Minimizing cost is a project goal, however this project calls for the creation of a prototype which could become very expensive. When smaller and more efficient components are used, the more expensive they become.

## II. Statement of Work:

### Method of Solution with Design Alternatives:

There are several ways to go about completing a vehicle to meet the design specifications; this made the final decision a difficult one to make. For each design aspect a number of choices were present, these areas include: launch specifications, type of propulsion, type of sensors, type of data processing, and power source. The following pages will go over the final design.

#### Launch Specifications

The first design challenge to consider is the launching method for the vehicle. To get the vehicle airborne, several methods can be employed, including traditional "runway" method, vertical take off, or assisted take offs through mortar/rocket launchers. The "runway" method is currently used by most major aircraft which involves a use of a straightaway to gain enough speed and lift to take the vehicle off the ground. The key strength to this method is the speed which the UAV could reach. This will allow it to travel further distances due to its initial speed and maximizing its fuel capacity. However, its key drawback is that an open area is required to launch the vehicle. Such an area is not always available, and it also poses a great risk to the launcher of the vehicle. Soldiers in an open field become much easier targets to snipers and other long range weapons then if they were in an area covered with camouflage or other obstacles. Vehicles of this launching method also tend to be much larger in size due to their wing span.

The assisted take off method is one of the new launch methods being used by the military. It includes the use of a container, which would house the UAV, designed to fit inside a mortar or rocket launcher. The soldier would fire the shell and shortly after becoming airborne, the shell would release and the UAV will begin taking reconnaissance of the area. Since takeoff is provided through external means, it allows for a much smaller UAV and faster deployment.

Although this method may seem very promising, there are some drawbacks to it. First is the durability of the design components. The speed at which a device comes out of a grenade/rocket launcher can reach speeds upwards of 255 meters/second[6]. This means the components must be able to withstand several Gs of force. Additionally, when firing off a mortar/rocket round, the location of the launch will be easily pinpointed by the enemy forces. As a result, when such a round is fired, the soldier will quickly have to leave the area before he comes under fire. Finally, this method requires the soldier having a mortar or rocket launcher with him, a device which most soldiers do not have immediate access to.

The final method is the vertical take off. This method is employed by helicopters and newer airplanes like the V-22 Osprey and AV-8 Harrier Jet. This allows for the vehicle to take off in a small area. The main draw backs of this method is the power required to get the vehicle off the ground is much greater then the other methods. In the end, this is the solution method used because it will enable the team to create a comparably small vehicle, while using rather low cost materials. Additionally, its ability to take off and maneuver in tight spaces will yield the versatility which the other methods do not provide.

Type of Propulsion

Having decided on a vertical take off system, there are a few ways this can be achieved. One of the oldest, most reliable and cheapest methods is to utilize a blimp. This method has a lower cost ratio then the other methods which will be introduced. Its major draw back is the size of the UAV. It will be of much larger size the other vehicles and is more susceptible to environmental conditions and detection. The slow movement speed and difficulty in deployment cannot be ignored either. Due to these reasons, this method was quickly dismissed.

This leaves two methods to be considered. The first is an open rotary system used by today's helicopters and the second is a ducted fan design. When comparing the two, it is noted that the ducted fan has the advantage of a greater thrust when comparing same diameter blades. To understand why this is true, one must look at the air flow of a ducted and open fan while it is in static condition (right before take off).

Figure 1: Open Propeller in Cruise Condition

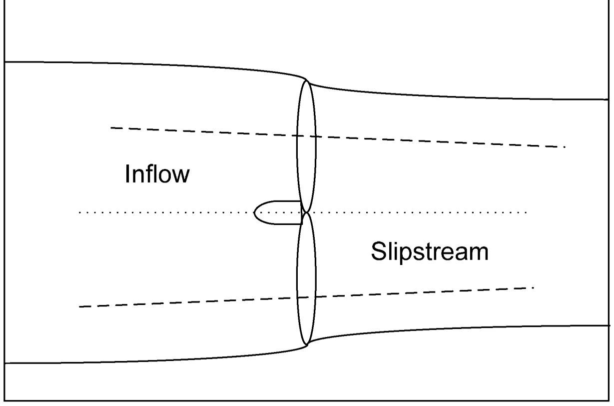
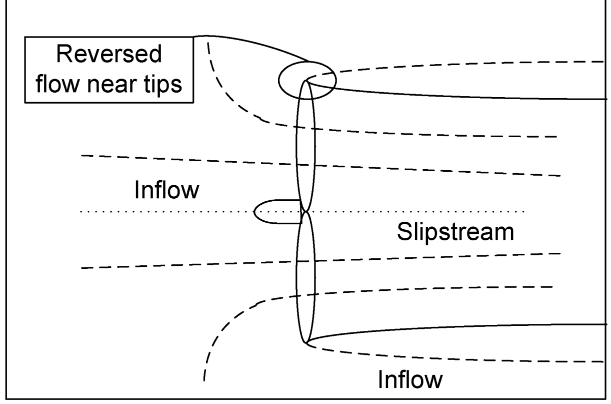



Figure 2: Open Propeller in Static Condition




In an open propeller system there are three major regions concerning the flow: “the inflow into the propeller, the slipstream behind it and the free stream which doesn’t go through the propeller” (see Figure 1)[3]. When the open propeller is viewed at a static state, the air flow regions change significantly. The slipstream region behind the propeller doesn’t change, but since the air is static, the free stream becomes the inflow region (see Figure 2). This forces the propeller to aspirate air not only from the front but also from the back of it. Due to this affect on the air particles, a region of reversed flow exists near the propeller tip. This phenomenon diminishes the effective disk area of the propeller, restricts the amount of air flow, and reduces its performance and efficiency. While the ducted fan system still has the same two flow regions (inflow, slipstream), it also has a solid boundary separating the two. This removes the effect of the phenomena and allows the ducted propeller to operate near its ideal operating point throughout the aircrafts operating speed range (see Figures 3 and 4).

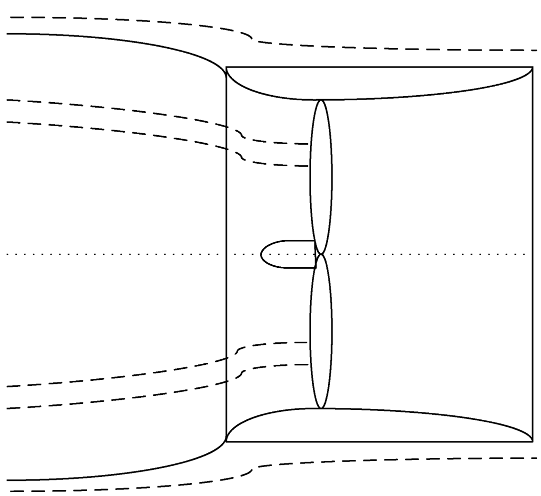


Figure 3: Ducted Fan in Cruise Condition

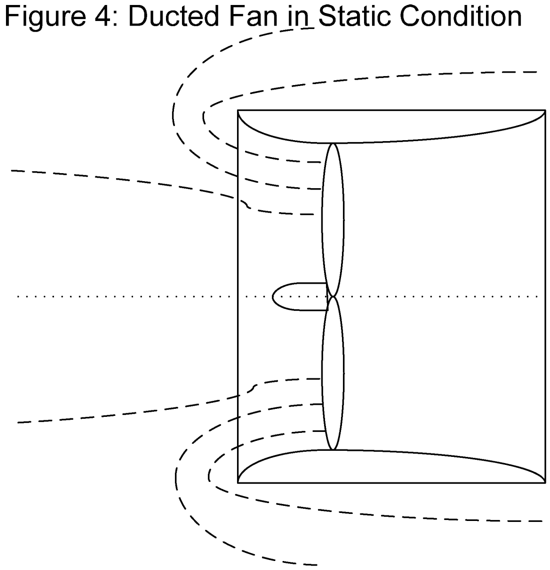


Figure 4: Ducted Fan in Static Condition

A duct around the fan also has the added benefit of shielding the fan from the harsh environment of the outside, and the fan "sees" air flowing in only one direction – front to rear and the effective diameter of the ducted propeller is larger than its physical diameter. There is also significant noise suppression in the ducted fan system, which is due to the elimination of the "Buzz" created by the open propeller tip, and the fact that the duct allows various acoustics treatments to absorb noise since a stealth flight is of importance.

<u>Type of Sensors</u>

In order to obtain a complete picture of the world, the vehicle will need to know several kinds of measurements – absolute position, relative position to objects in proximity, speed, pitch/yaw/roll and direction of flight.

Absolute position is very important in maintaining a course and fulfilling mission objectives for the UAV. There are relatively little options available to accurately measure one's position, the best one being a GPS system. Today's GPS devices are capable of pinpointing the location within feet of the actual position, which is more than enough for the design.

Relative position to any possible obstacles can be obtained using proximity sensors. There are four different types of proximity sensors available – infrared, sonar, capacitive and inductive. With the wide variety of sensor types available, it is important to recognize the advantages and capabilities of each one.

Capacitive sensors detect proximity by measuring changes in charge around them. This type of sensor, however, can give very different results depending on the dielectric constant of the target, and thus is not very useful for the design purposes.

Inductive sensors detect proximity by sensing magnetic fields, and are especially sensitive to metals. Because the main goal is distance detection, this property is actually detrimental and this type of sensor is not very useful in the proposed design as well.

Infrared sensors can measure distance with great accuracy, and their accuracy is only slightly affected by ambient temperature and other environmental changes. Infrared emission from the target does affect the readings however, but this can be fixed through utilization of triangulation. An example of such a sensor is Sharp GP2D12 IR Ranger. The problem with Infrared sensors is that they have somewhat limited range. The given sensor can only distinguish ranges between 10cm and 80cm, giving it less then an order of magnitude difference between minimum and maximum ranges. And such performance is typical of all infrared sensors. A sensor with smaller minimum range, and longer maximum range than the current IR sensors can offer to meet the design goals.

Sonar sensors, specifically ultrasonic sensors, are also capable of precise measurements, much like the infrared sensors. Unlike the IR sensors, ultrasonic ones have a greater range. For example, Devantech SRF08 sensor can accurately measure distances between 3cm and 6m. This type of distance should be adequate for the design. Considering that the costs and sizes of IR and ultrasonic sensors are very comparable, the team decided to utilize the ultrasonic sensors as proximity detectors.

Direction of flight and vehicle's tilt can be measured by a single magnetic sensor. Being an industry standard for many years, these sensors are getting smaller and smaller, and today one can easily fit one of these sensors onboard the UAV. The team was provided with a particular model, Honeywell Three-Axis Magnetoresistive Sensor HMC1023, which will create analog output that can be converted to digital using microcontroller's on-board converter.

Since the aircraft will need to fly in various conditions and locations, it is important to know the speed that this vehicle might acquire. This speed can be calculated with help of accelerometers. Accelerometers today are capable or very precise results and very small sizes, which is exactly what is necessary for the design. A specific model that suits the design is

ADXL105AQC by Analog Devices, which is capable of dynamic and static acceleration measurement.

Type of Data Processing

All the sensory data will have to be processed using some type of a controller. It has to be fast in order to process the data that is constantly streaming from all the sensors. It also has to be small enough to be carried aboard the UAV. And with various high-priced controller systems, the team would also like to minimize the cost of such a controller. After comparing various options, such as Motorola 68HC11 chip, the team found a good alternative – Atmel ATMega16 microcontroller, which is powerful, small in size and affordable. It also has an on-board analog to digital converter, which is very useful when dealing with various analog sensors.

Power Source

Due to the size limitations of the project, the only real option remaining is battery powered devices. Gas and other type of power sources are not only much heavier but also put out a lot more noise then their silent battery counterparts. Since the power source has to be reusable, a rechargeable batter was the only option. This left the team with 3 viable choices: Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), and Lithium Ion Polymer (Li-Poly). Nickel Cadmium is the most popular rechargeable battery in the industry today. Its advantages include high number of charge/discharge cycles (up to several thousand if properly maintained) and the only battery type that performs well when periodically fully discharged. NiCd also has the very low self discharge rate (rate at which the battery loses power under no use), coming in around 10.0% per month and takes the least amount of time to fully charge (~90minutes). While Nickel Metal Hydride has 30% more capacity then NiCd, it also has a much shorter charge/discharge life (around 400-700 cycles) and requires almost two times as long to charge. This, compounded with its 30.0% per month self discharge rate, puts it behind the NiCd in terms of battery choice. The final choice is the Lithium Ion Polymer. Its two weaknesses are its very low cycle count (150-300 cycles), and long recharge time (8-16hours). Even with these two down sides, this battery has three major strengths to it. It is the lightest battery out of the group and has two times the energy density of NiCd. It also has the lowest self discharge rate, coming in at 0.2% per year. These two major strengths offset its two weaknesses and make this the best choice for a battery.

**Prototype Testing and Validation:**

The current ducted fan prototype will consist of four ducted fans used primarily for radio controlled jet flight. The current model being investigated is the VAS400G (Vasafan 65/1G) ducted fan assembly and driven by either a Graupner GR3321 (Speed 400) or GR6330 (Speed 480) motor. The data sheet for the motor and fan is available in Appendix F. The prototype concept consists of four ducted fan assemblies in which two fans will rotate clockwise and the other two will rotate counterclockwise; preventing rotation of the vehicle about its vertical axis. The magnetoresistive and accelerometer sensors will be placed on a central circuit board with the ATMega16 microcontroller onboard the aircraft. Tests will be run in order to see how much power is required to lift the aircraft off the ground and maintain its flight. After the controller and sensor circuitry has been added to the aircraft testing of the control algorithm will take place. The purpose of the second test phase is to see if the ducted fan vehicle can maintain a level position at a specific altitude. The results of the testing will be verified by a mathematical model of the system written using the ProPac add-on to Mathematica.

**Market Studies:**

Currently, there exists one product which has similar design to the team's idea, called Draganflyer[7]. It is a four-bladed flying apparatus, which utilizes open rotor blades and electric motors for propulsion. While it is remotely controlled, it utilizes a controller to stabilize and maneuver the aircraft. For power supply, it utilizes Lithium-Polymer rechargeable batteries, and can lift up to 4 ounces.

As a commercial product, this seems to be a very interesting device; however, there are some key differences between the proposed design and the Draganflyer. The open blade design can be dangerous, and is noisier as well. Also, the whole unit is remotely controlled, while the proposed UAV will be autonomous, with minimal interference by humans.

**III. Project Management/Timeline:**

The project team is composed of two mechanical engineers, one electrical engineer, and a computer engineer. The résumés of each team member are available in Appendix G. A project timeline in the form of a Gantt chart is also available in Appendix A. Key components of the project include selecting and testing a ducted fan to see if it can lift itself off the ground under its own power, procuring the fan with motor, developing a mathematical model for the design, and creating the control algorithm necessary to keep the ducted fan aircraft in stable, level flight.

## IV. Economic Analysis:

Funding for the project is provided through the United States Army at Aberdeen Proving Grounds in the amount of $2,000. The costs of the project include purchasing ducted fan assemblies with motors, sensors, Atmel AVR Mega16 microcontroller, circuit board, and parts needed to connect the ducted fans together into one assembly. A budget is available in Appendix B that outlines the cost of each component and engineering services. The data sheets for the microcontroller and sensors are available in Appendices C, D, and E.

## V. Societal and Environmental Impact:

The ducted fan aircraft is designed with the intent to be used for military reconnaissance. The importance of having good intelligence on the field is crucial in ensuring that the lives of soldiers on the battlefield will not be needlessly endangered. It would be beneficial for such a device to be deployed, perform its mission, and return to its owner's hands ready to be reused. Therefore it is imperative that a successful control algorithm be developed to ensure that the vehicle returns safely to its user. The aircraft is intended to be reusable; therefore there is no solid waste or byproducts generated. Electric motors powered by rechargeable batteries are used to propel the vehicle, so that no air pollution is generated. Overall the ducted fan aircraft has minimal environmental impact.

Ducted fan propelled aircraft do have useful civilian applications. Such an aircraft could be used for geological surveys of volcanoes or other areas that are unsafe for humans to traverse. The information that could be collected from such a vehicle may be valuable to geologists attempting to predict seismic activity. Another application could be in search and rescue operations in wildfires or collapsed buildings in which the vehicle could help rescuers determine a safe path to reach the trapped victims. An aircraft propelled by ducted fans could also be used for building inspection for high rise buildings or skyscrapers where it is difficult to send people to the building exterior on the upper floors. In addition to the military uses of the aircraft, it would be beneficial in the commercial environment to use these vehicles.

## VI. Summary and Conclusions

The main purpose of the design is to create an unmanned aerial vehicle capable of real-time position measurement and self-control. To design such a vehicle, several key points were discussed including launch specifications, type of propulsion, type of sensors, type of data processing, and power source. From these 5 major areas, it was found a ducted fan vehicle capable of vertical take off would best fit the design objective. To obtain self control, vehicle data such as such as absolute position, relative position to objects in proximity, speed, pitch/yaw/roll and direction of flight are needed. These can be found by using a GPS system, ultrasonic sensors, Honeywell Three-Axis Magnetoresistive Sensor HMC1023, and the ADXL105AQC by Analog Devices. Finally, to process all this data, the Atmel ATMega16 microcontroller will be used for data analysis and processing. Using these components the team should be able to fabricate a viable prototype.

## VII. References:

[1] AVR STK500 User Guide, Atmel, version 1925C, 2003.

[2] Barnett R., Cox S., and O'Cull L., 2003, *Embedded C Programming and the Atmel AVR*. Thomson Delmar Learning, Canada.

[3] de Piolence, M. F., Wright, G.E. Jr., 2001, Ducted Fan Design Volume 1.

[4] Analog Devices. ADXL105 Products Page. 14 November 2003. [Online] Available: http://www.analog.com/Analog_Root/productPage/productHome/0%2C%2CADXL105%2C00.html

[5] Honeywell International. Magnetic Sensors, Magnetometers, Magnetic Field Sensing. 14 November 2003. [Online] Available: http://www.magneticsensors.com

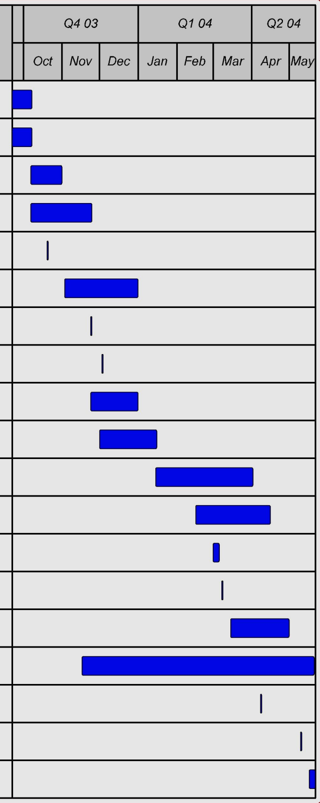
[6] British Army. Infantry: 81mm L16 Mortar. 2003. [Online] Available: http://www.armedforces.co.uk/army/listings/l0098.html

[7] RCToys. Draganflyer IV: 2003. [Online] Available: http://www.rctoys.com/draganflyer4.php

# VIII. Appendices

# A: Gantt Chart

| ID | Task Name | Start | Finish | Duration |
|---|---|---|---|---|
| 1 | Research Uses of Ducted Fan | 9/22/2003 | 10/7/2003 | 12d |
| 2 | Research Ducted Fan Design Parameters | 9/22/2003 | 10/7/2003 | 12d |
| 3 | Procure a ducted fan for testing | 10/7/2003 | 10/31/2003 | 19d |
| 4 | Investigate sensors | 10/7/2003 | 11/24/2003 | 35d |
| 5 | Pre-Proposal Due | 10/20/2003 | 10/20/2003 | 1d |
| 6 | Initial Testing of Ducted Fan | 11/3/2003 | 12/31/2003 | 43d |
| 7 | Proposal Due | 11/24/2003 | 11/24/2003 | 1d |
| 8 | Proposal Presentation | 12/3/2003 | 12/3/2003 | 1d |
| 9 | Procure additional fans and build prototype vehicle | 11/24/2003 | 12/31/2003 | 28d |
| 10 | Develop dynamics model of system | 12/1/2003 | 1/15/2004 | 34d |
| 11 | Build sensor/controller circuits | 1/15/2004 | 4/1/2004 | 56d |
| 12 | Develop AVR code | 2/16/2004 | 4/15/2004 | 44d |
| 13 | Status Report Presentations | 3/1/2004 | 3/5/2004 | 5d |
| 14 | Status Report Due | 3/8/2004 | 3/8/2004 | 1d |
| 15 | Implement Sensor/Controller Design | 3/15/2004 | 4/30/2004 | 35d |
| 16 | Testing and Demonstration of Ducted Fan Aircraft | 11/17/2003 | 5/20/2004 | 134d |
| 17 | Senior Design Abstract Due | 4/8/2004 | 4/8/2004 | 1d |
| 18 | Final Senior Design Report Due | 5/10/2004 | 5/10/2004 | 1d |
| 19 | Final Senior Design Presentation | 5/17/2004 | 5/21/2004 | 5d |



**Appendix B: Economic Analysis/Budget**

| **Budget for Building Concept-Demonstration Prototype** | | | | |
|---|---|---|---|---|
| **Description** | **Qty** | **Unit** | **Cost Per** | **Actual Cost** |
| VAS400G Ducted Fan Assembly | 4 | Each | $ 89.90 | $ 359.60 |
| ATMEL STK500 Microcontroller Kit | 1 | Each | $ 80.00 | $ 80.00 |
| Accelerometer Sensor (ADXL105QC) | 1 | Each | $ 23.94 | $ 23.94 |
| Magnetometer Sensor (HMC1023) | 1 | Each | $ 100.00 | $ 100.00 |
| Speed 480 (GR6330) | 4 | Each | $ 24.50 | $ 98.00 |
| H-Bridges | 1 | Each | $ 20.00 | $ 20.00 |
| Connector, Pin, Fem | 1 | Pack | $ 11.05 | $ 11.05 |
| Radio Shack - Sockets, Wires, Capacitors, Resistors | 1 | Pack | $ 57.57 | $ 57.57 |
| Voltage Regulators | 1 | Each | $ 20.00 | $ 20.00 |
| **Total** | | | | **$ 770.16** |

| **Budget for Engineering Development Project** | | | | | |
|---|---|---|---|---|---|
| **Description** | **Qty** | **Unit** | **Cost Per** | **Actual Cost** | **Out of Pocket** |
| VAS400G Ducted Fan Assembly | 4 | Each | $ 89.90 | $ 359.60 | $ 0.00 |
| ATMEL STK500 Microcontroller Kit | 1 | Each | $ 80.00 | $ 80.00 | $ 80.00 |
| Accelerometer Sensor (ADXL105QC) | 1 | Each | $ 23.94 | $ 23.94 | $ 0.00 |
| Magnetometer Sensor (HMC1023) | 1 | Each | $ 100.00 | $ 100.00 | $ 0.00 |
| Graupner GR3321 Speed 400 motor | 1 | Each | $ 9.50 | $ 9.50 | $ 0.00 |
| Graupner GR6330 Speed 480 motor | 4 | Each | $ 24.50 | $ 98.00 | $ 0.00 |
| H-Bridges | 1 | Each | $ 20.00 | $ 20.00 | $ 0.00 |
| Connector, Pin, Fem | 1 | Pack | $ 11.05 | $ 11.05 | $ 0.00 |
| Radio Shack - Sockets, Wires, Capacitors, Resistors | 1 | Pack | $ 57.57 | $ 57.57 | $ 0.00 |
| Laboratory Tools | 1 | Lot | $ 200.00 | $ 200.00 | $ 0.00 |
| Office Supplies | 1 | Lot | $ 200.00 | $ 200.00 | $ 0.00 |
| **Total** | | | | **$ 1,159.66** | **$ 80.00** |

| **Industry Budget** | | | |
|---|---|---|---|
| | **Cost per Unit** | **Total Units** | **Total Cost** |
| **Employees** | | | |
| Mechanical Engineer | $30.00 / hour | 340 hours | $ 10,200.00 |
| Electrical Engineer | $35.00 / hour | 340 hours | $ 11,900.00 |
| Computer Engineer | $30.00 / hour | 340 hours | $ 10,200.00 |
| Project Manager | $50.00 / hour | 340 hours | $ 17,000.00 |
| **Software Licensing** | $7,000.00 | 1 | $ 7,000.00 |
| **Materials** | $770.16 | 1 | $ 770.16 |
| **Total Labor, Software, Materials** | | | $ 57,070.16 |
| **Overhead @ 100%** | | | $ 57,070.16 |
| **Total Industrial Budget** | | | **$ 114,140.32** |

# C: Atmel AVR ATMega16 Data Sheet

## Features

- High-performance, Low-power AVR® 8-bit Microcontroller
- Advanced RISC Architecture
  - 131 Powerful Instructions – Most Single-clock Cycle Execution
  - 32 x 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 16 MIPS Throughput at 16 MHz
  - On-chip 2-cycle Multiplier
- Nonvolatile Program and Data Memories
  - 16K Bytes of In-System Self-Programmable Flash
    Endurance: 10,000 Write/Erase Cycles
  - Optional Boot Code Section with Independent Lock Bits
    In-System Programming by On-chip Boot Program
    True Read-While-Write Operation
  - 512 Bytes EEPROM
    Endurance: 100,000 Write/Erase Cycles
  - 1K Byte Internal SRAM
  - Programming Lock for Software Security
- JTAG (IEEE std. 1149.1 Compliant) Interface
  - Boundary-scan Capabilities According to the JTAG Standard
  - Extensive On-chip Debug Support
  - Programming of Flash, EEPROM, Fuses, and Lock Bits through the JTAG Interface
- Peripheral Features
  - Two 8-bit Timer/Counters with Separate Prescalers and Compare Modes
  - One 16-bit Timer/Counter with Separate Prescaler, Compare Mode, and Capture Mode
  - Real Time Counter with Separate Oscillator
  - Four PWM Channels
  - 8-channel, 10-bit ADC
    8 Single-ended Channels
    7 Differential Channels in TQFP Package Only
    2 Differential Channels with Programmable Gain at 1x, 10x, or 200x
  - Byte-oriented Two-wire Serial Interface
  - Programmable Serial USART
  - Master/Slave SPI Serial Interface
  - Programmable Watchdog Timer with Separate On-chip Oscillator
  - On-chip Analog Comparator
- Special Microcontroller Features
  - Power-on Reset and Programmable Brown-out Detection
  - Internal Calibrated RC Oscillator
  - External and Internal Interrupt Sources
  - Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby and Extended Standby
- I/O and Packages
  - 32 Programmable I/O Lines
  - 40-pin PDIP, 44-lead TQFP, and 44-pad MLF
- Operating Voltages
  - 2.7 - 5.5V for ATmega16L
  - 4.5 - 5.5V for ATmega16
- Speed Grades
  - 0 - 8 MHz for ATmega16L
  - 0 - 16 MHz for ATmega16
- Power Consumption @ 1 MHz, 3V, and 25°C for ATmega16L
  - Active: 1.1 mA
  - Idle Mode: 0.35 mA
  - Power-down Mode: < 1 µA

8-bit AVR®
Microcontroller
with 16K Bytes
In-System
Programmable
Flash

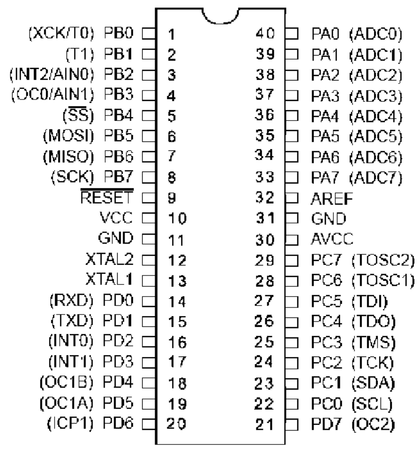
ATmega16
ATmega16L

2466G–AVR–10/03

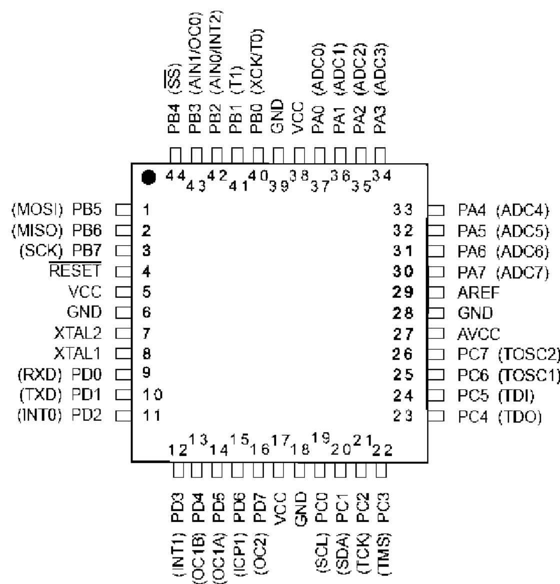
## Pin Configurations

**Figure 1.** Pinouts ATmega16

PDIP




TQFP/MLF




## Disclaimer

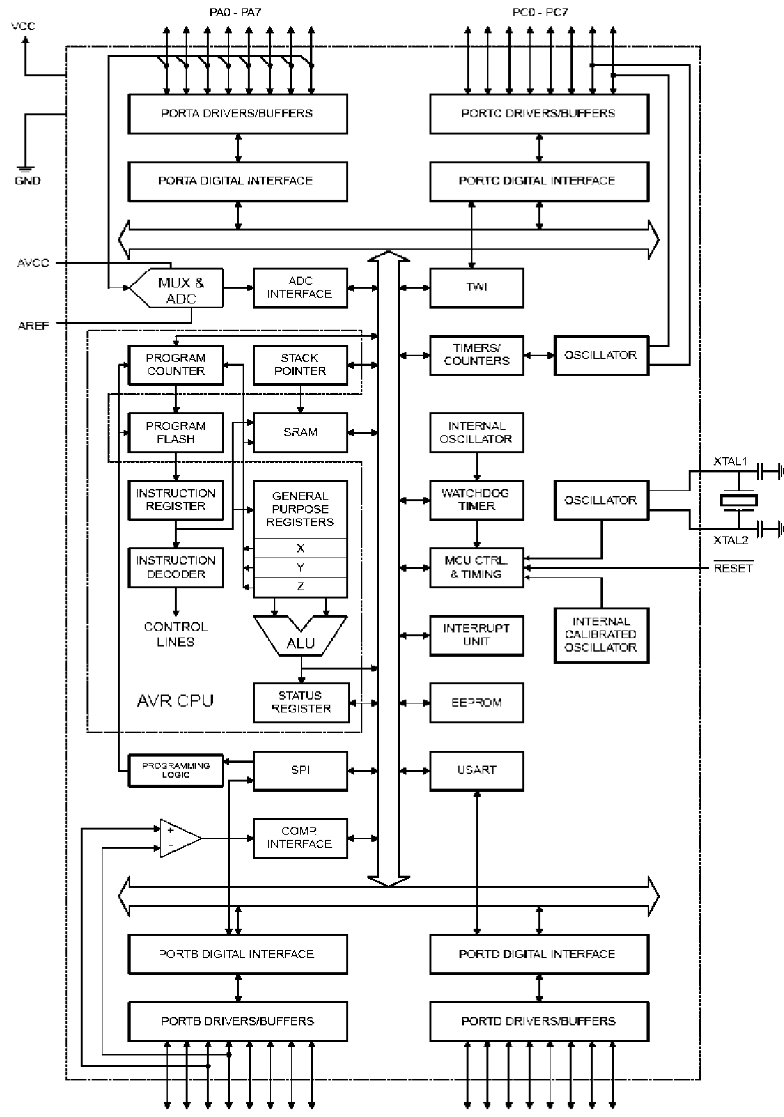
Typical values contained in this datasheet are based on simulations and characterization of other AVR microcontrollers manufactured on the same process technology. Min and Max values will be available after the device is characterized.

## Overview

The ATmega16 is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the ATmega16 achieves throughputs approaching 1 MIPS per MHz allowing the system designer to optimize power consumption versus processing speed.

## Block Diagram

**Figure 2.** Block Diagram



The AVR core combines a rich instruction set with 32 general purpose working registers. All the 32 registers are directly connected to the Arithmetic Logic Unit (ALU), allowing two independent registers to be accessed in one single instruction executed in one clock cycle. The resulting architecture is more code efficient while achieving throughputs up to ten times faster than conventional CISC microcontrollers.

The ATmega16 provides the following features: 16K bytes of In-System Programmable Flash Program memory with Read-While-Write capabilities, 512 bytes EEPROM, 1K byte SRAM, 32 general purpose I/O lines, 32 general purpose working registers, a JTAG interface for Boundary-scan, On-chip Debugging support and programming, three flexible Timer/Counters with compare modes, Internal and External Interrupts, a serial programmable USART, a byte oriented Two-wire Serial Interface, an 8-channel, 10-bit ADC with optional differential input stage with programmable gain (TQFP package only), a programmable Watchdog Timer with Internal Oscillator, an SPI serial port, and six software selectable power saving modes. The Idle mode stops the CPU while allowing the USART, Two-wire interface, A/D Converter, SRAM, Timer/Counters, SPI port, and interrupt system to continue functioning. The Power-down mode saves the register contents but freezes the Oscillator, disabling all other chip functions until the next External Interrupt or Hardware Reset. In Power-save mode, the Asynchronous Timer continues to run, allowing the user to maintain a timer base while the rest of the device is sleeping. The ADC Noise Reduction mode stops the CPU and all I/O modules except Asynchronous Timer and ADC, to minimize switching noise during ADC conversions. In Standby mode, the crystal/resonator Oscillator is running while the rest of the device is sleeping. This allows very fast start-up combined with low-power consumption. In Extended Standby mode, both the main Oscillator and the Asynchronous Timer continue to run.

The device is manufactured using Atmel's high density nonvolatile memory technology. The On-chip ISP Flash allows the program memory to be reprogrammed in-system through an SPI serial interface, by a conventional nonvolatile memory programmer, or by an On-chip Boot program running on the AVR core. The boot program can use any interface to download the application program in the Application Flash memory. Software in the Boot Flash section will continue to run while the Application Flash section is updated, providing true Read-While-Write operation. By combining an 8-bit RISC CPU with In-System Self-Programmable Flash on a monolithic chip, the Atmel ATmega16 is a powerful microcontroller that provides a highly-flexible and cost-effective solution to many embedded control applications.

The ATmega16 AVR is supported with a full suite of program and system development tools including: C compilers, macro assemblers, program debugger/simulators, in-circuit emulators, and evaluation kits.

## Pin Descriptions

**VCC**

Digital supply voltage.

**GND**

Ground.

**Port A (PA7..PA0)**

Port A serves as the analog inputs to the A/D Converter.

Port A also serves as an 8-bit bi-directional I/O port, if the A/D Converter is not used. Port pins can provide internal pull-up resistors (selected for each bit). The Port A output buffers have symmetrical drive characteristics with both high sink and source capability. When pins PA0 to PA7 are used as inputs and are externally pulled low, they will source current if the internal pull-up resistors are activated. The Port A pins are tri-stated when a reset condition becomes active, even if the clock is not running.

**Port B (PB7..PB0)**

Port B is an 8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port B output buffers have symmetrical drive characteristics with both high sink and source capability. As inputs, Port B pins that are externally pulled low will source current if the pull-up resistors are activated. The Port B pins are tri-stated when a reset condition becomes active, even if the clock is not running.

Port B also serves the functions of various special features of the ATmega16 as listed on page 56.

**Port C (PC7..PC0)**

Port C is an 8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port C output buffers have symmetrical drive characteristics with both high sink and source capability. As inputs, Port C pins that are externally pulled low will source current if the pull-up resistors are activated. The Port C pins are tri-stated when a reset condition becomes active, even if the clock is not running. If the JTAG interface is enabled, the pull-up resistors on pins PC5(TDI), PC3(TMS) and PC2(TCK) will be activated even if a reset occurs.

Port C also serves the functions of the JTAG interface and other special features of the ATmega16 as listed on page 59.

**Port D (PD7..PD0)**

Port D is an 8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port D output buffers have symmetrical drive characteristics with both high sink and source capability. As inputs, Port D pins that are externally pulled low will source current if the pull-up resistors are activated. The Port D pins are tri-stated when a reset condition becomes active, even if the clock is not running.

Port D also serves the functions of various special features of the ATmega16 as listed on page 61.

**$\overline{\text{RESET}}$**

Reset Input. A low level on this pin for longer than the minimum pulse length will generate a reset, even if the clock is not running. The minimum pulse length is given in Table 15 on page 36. Shorter pulses are not guaranteed to generate a reset.

**XTAL1**

Input to the inverting Oscillator amplifier and input to the internal clock operating circuit.

**XTAL2**

Output from the inverting Oscillator amplifier.

**AVCC**

AVCC is the supply voltage pin for Port A and the A/D Converter. It should be externally connected to $V_{CC}$, even if the ADC is not used. If the ADC is used, it should be connected to $V_{CC}$ through a low-pass filter.

**AREF**

AREF is the analog reference pin for the A/D Converter.

## About Code Examples

This documentation contains simple code examples that briefly show how to use various parts of the device. These code examples assume that the part specific header file is included before compilation. Be aware that not all C Compiler vendors include bit definitions in the header files and interrupt handling in C is compiler dependent. Please confirm with the C Compiler documentation for more details.

## Appendix D: Analog Devices ADXL105 Datasheet

ANALOG DEVICES

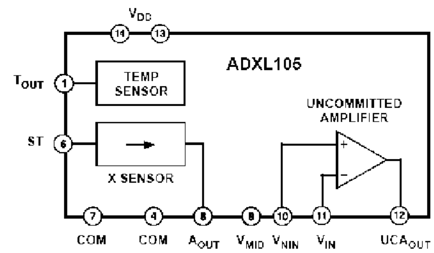
# High Accuracy ±1 *g* to ±5 *g* Single Axis *i*MEMS® Accelerometer with Analog Input

# ADXL105*

**FEATURES**
**Monolithic IC Chip**
**2 m*g* Resolution**
**10 kHz Bandwidth**
**Flat Amplitude Response (±1%) to 5 kHz**
**Low Bias and Sensitivity Drift**
**Low Power 2 mA**
**Output Ratiometric to Supply**
**User Scalable *g* Range**
**On-Board Temperature Sensor**
**Uncommitted Amplifier**
**Surface Mount Package**
**+2.7 V to +5.25 V Single Supply Operation**
**1000 *g* Shock Survival**

**APPLICATIONS**
**Automotive**
**Accurate Tilt Sensing with Fast Response**
**Machine Health and Vibration Measurement**
**Affordable Inertial Sensing of Velocity and Position**
**Seismic Sensing**
**Rotational Acceleration**

**FUNCTIONAL BLOCK DIAGRAM**




**GENERAL DESCRIPTION**

The ADXL105 is a high performance, high accuracy and complete single-axis acceleration measurement system on a single monolithic IC. The ADXL105 offers significantly increased bandwidth and reduced noise versus previously available micromachined devices. The ADXL105 measures acceleration with a full-scale range up to ±5 *g* and produces an analog voltage output. Typical noise floor is 225 μ*g*/√Hz allowing signals below 2 m*g* to be resolved. A 10 kHz wide frequency response enables vibration measurement applications. The product exhibits significant reduction in offset and sensitivity drift over temperature compared to the ADXL05.

The ADXL105 can measure both dynamic accelerations, (typical of vibration) or static accelerations (such as inertial force, gravity or tilt).

Output scale factors from 250 mV/*g* to 1.5 V/*g* are set using the on-board uncommitted amplifier and external resistors. The device features an on-board temperature sensor with an output of 8 mV/°C for optional temperature compensation of offset vs. temperature for high accuracy application.

The ADXL105 is available in a hermetic 14-lead surface mount Cerpak with versions specified for the 0°C to +70°C, and −40°C to +85°C temperature ranges.

*Patent Pending.
*i*MEMS is a registered trademark of Analog Devices, Inc.

REV. A



One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781/329-4700 World Wide Web Site: http://www.analog.com
Fax: 781/326-8703 

# ADXL105–SPECIFICATIONS ($T_A = T_{MIN}$ to $T_{MAX}$, $T_A = +25°C$ for J Grade Only, $V_S = +5$ V, @ Acceleration = 0 *g*, unless otherwise noted)

| Parameter | Conditions | ADXL105J/A Min | Typ | Max | Units |
|---|---|---|---|---|---|
| SENSOR INPUT | | | | | |
| Measurement Range[1] | | ±5 | ±7 | | *g* |
| Nonlinearity | Best Fit Straight Line | | 0.2 | | % of FS |
| Alignment Error[2] | | | ±1 | | Degrees |
| Cross Axis Sensitivity[3] | Z Axis, @ +25°C | | ±1 | ±5 | % |
| SENSITIVITY[1] (Ratiometric) | At $A_{OUT}$ | | | | |
| Initial | | 225 | 250 | 275 | mV/*g* |
| | $V_S = 2.7$ V | 80 | 105 | 120 | mV/*g* |
| vs. Temperature[5, 6] | | | ±0.5 | | % |
| ZERO *g* BIAS LEVEL[5] (Ratiometric) | At $A_{OUT}$ | | | | |
| Zero *g* Offset Error | From +2.5 V Nominal | –625 | | +625 | mV |
| vs. Supply | | –20 | | +20 | mV/$V_{DD}$/V |
| vs. Temperature[5, 7] | | | 50 | | mV |
| NOISE PERFORMANCE | | | | | |
| Voltage Density[7] | @ +25°C | | 225 | 325 | $\mu g/\sqrt{Hz}$ |
| Noise in 100 Hz Bandwidth | | | 2.25 | | m*g* rms |
| FREQUENCY RESPONSE | | | | | |
| 3 dB Bandwidth | | 10 | 12 | | kHz |
| Sensor Resonant Frequency | | 13 | 18 | | kHz |
| TEMP SENSOR[4] (Ratiometric) | | | | | |
| Output Error at +25°C | From +2.5 V Nominal | –100 | | +100 | mV |
| Nominal Scale Factor | | | 8 | | mV/°C |
| Output Impedance | | | 10 | | kΩ |
| $V_{MID}$[4] (Ratiometric) | | | | | |
| Output Error | From +2.5 V Nominal | –15 | | +15 | mV |
| Output Impedance | | | 10 | | kΩ |
| SELF-TEST (Proportional to $V_{DD}$) | | | | | |
| Voltage Delta at $A_{OUT}$ | Self-Test "0" to "1" | 100 | | 500 | mV |
| Input Impedance[8] | | 30 | 50 | | kΩ |
| $A_{OUT}$ | | | | | |
| Output Drive | I = ±50 µA | 0.50 | | $V_S - 0.5$ | V |
| Capacitive Load Drive | | 1000 | | | pF |
| UNCOMMITTED AMPLIFIER | | | | | |
| Initial Offset | | –25 | | +25 | mV |
| Initial Offset vs. Temperature | | | 5 | | µV/°C |
| Common-Mode Range | | 1.0 | | 4.0 | V |
| Input Bias Current[9] | | | 25 | | nA |
| Open Loop Gain | | | 100 | | V/mV |
| Output Drive | I = ±100 µA | 0.25 | | $V_S - 0.25$ | V |
| Capacitive Load Drive | | 1000 | | | pF |
| POWER SUPPLY | | | | | |
| Operating Voltage Range | | 2.70 | | 5.25 | V |
| Quiescent Supply Current | At 5.0 V | | 1.9 | 2.6 | mA |
| | At 2.7 V | | 1.3 | 2.0 | mA |
| Turn-On Time | | | 700 | | µs |
| TEMPERATURE RANGE | | | | | |
| Operating Range J | | 0 | | +70 | °C |
| Specified Performance A | | –40 | | +85 | °C |

NOTES

[1]Guaranteed by tests of zero *g* bias, sensitivity and output swing.

[2]Alignment of the X axis is with respect to the long edge of the bottom half of the Cerpak package.

[3]Cross axis sensitivity is measured with an applied acceleration in the Z axis of the device.

[4]This parameter is ratiometric to the supply voltage $V_{DD}$. Specification is shown with a 5.0 V $V_{DD}$. To calculate approximate values at another $V_{DD}$, multiply the specification by $V_{DD}$/5 V.

[5]Specification refers to the maximum change in parameter from its initial value at +25°C to its worst case value at $T_{MIN}$ to $T_{MAX}$.

[6]See Figure 3.

[7]See Figure 2.

[8]CMOS and TTL Compatible.

[9]UCA input bias current is tested at final test.

All min and max specifications are guaranteed. Typical specifications are not tested or guaranteed.

Specifications subject to change without notice.

**ABSOLUTE MAXIMUM RATINGS***

Acceleration (Any Axis, Unpowered for 0.5 ms) . . . . . . 1000 *g*
Acceleration (Any Axis, Powered for 0.5 ms) . . . . . . . . . 500 *g*
$+V_S$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . –0.3 V to +7.0 V
Output Short Circuit Duration
(Any Pin to Common) . . . . . . . . . . . . . . . . . . . . Indefinite
Operating Temperature . . . . . . . . . . . . . . . . –55°C to +125°C
Storage Temperature . . . . . . . . . . . . . . . . . . –65°C to +150°C

*Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; the functional operation of the device at these or any other conditions above those indicated in the operational sections of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

Package Characteristics

| Package | $\theta_{JA}$ | $\theta_{JC}$ | Device Weight |
|---|---|---|---|
| 14-Lead Cerpak | 110°C/W | 30°C/W | <2 Grams |

**ORDERING GUIDE**

| Model | Temperature Range | Package Option |
|---|---|---|
| ADXL105JQC | 0°C to +70°C | QC-14 |
| ADXL105AQC | –40°C to +85°C | QC-14 |

CAUTION

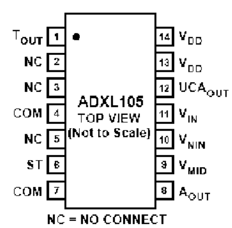
ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the ADXL105 features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.


Drops onto hard surfaces can cause shocks of greater than 1000 *g* and exceed the absolute maximum rating of the device. Care should be exercised in handling to avoid damage.

**PIN FUNCTION DESCRIPTIONS**

| Pin No. | Name | Description |
|---|---|---|
| 1 | $T_{OUT}$ | Temperature Sensor Output |
| 2, 3, 5 | NC | No Connect |
| 4 | COM | Common |
| 6 | ST | Self-Test |
| 7 | COM | Common (Substrate) |
| 8 | $A_{OUT}$ | Accelerometer Output |
| 9 | $V_{MID}$ | $V_{DD}/2$ Reference Voltage |
| 10 | $V_{NIN}$ | Uncommitted Amp Noninverting Input |
| 11 | $V_{IN}$ | Uncommitted Amp Inverting Input |
| 12 | $UCA_{OUT}$ | Uncommitted Amp Output |
| 13, 14 | $V_{DD}$ | Power Supply Voltage |

**PIN CONFIGURATION**



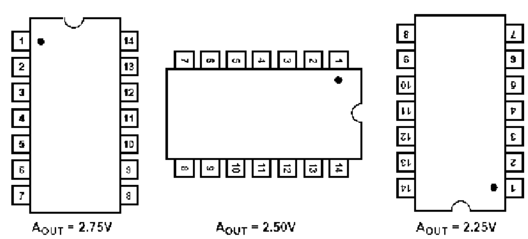




*Figure 1. ADXL105 Response Due to Gravity*

**Appendix E: Honeywell HMC1023 Three-Axis Magnetoresistive Sensor Datasheet**

Honeywell

SENSOR PRODUCTS

*Advance Information*

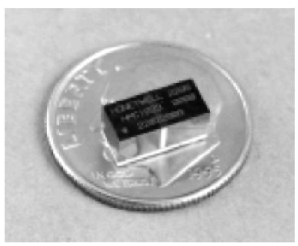
**APPLICATIONS**

- Compassing
- Navigation Systems
- Attitude Reference
- Virtual Reality
- Traffic Detection
- Proximity Detection
- Medical Devices

# Three-Axis Magnetoresistive Sensor

## HMC1023


*Not actual size*

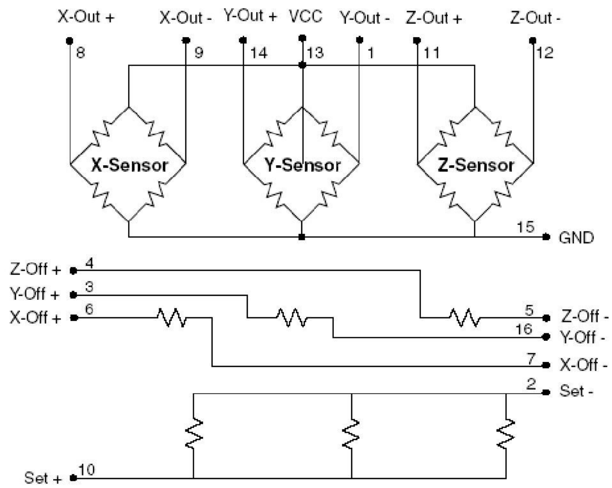


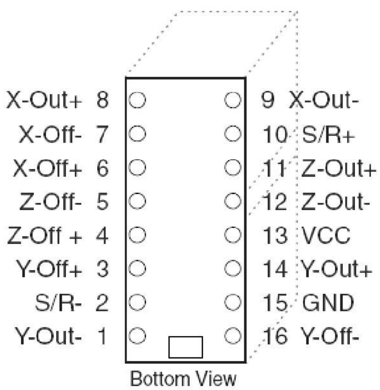
Configured as three magnetoresistive sensors in x, y and z orientation, these highly sensitive sensors convert all three magnetic field axes to a differential output voltage. This new addition to our line of magnetoresistive sensors is smaller, uses less power and is ideal for applications that require orthogonal three-axis sensing.

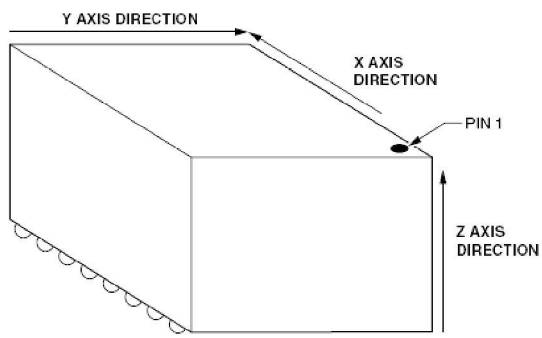
## FEATURES AND BENEFITS

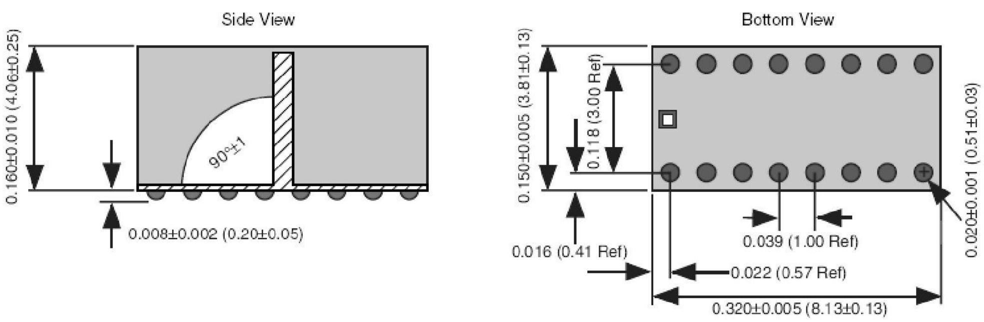
| | |
|---|---|
| **Wide Field Range** | Field range of ±6 gauss, (earth's field = 0.5 gauss) while maintaining high sensitivity with a minimal detectable field down to 85 µgauss. |
| **Small Package** | Designed to work as a single stand alone three-axis (x,y,z) magnetoresistive sensing system. Custom Ball Grid Array (BGA), 1mm pitch, 16-pin miniature package provides a small footprint and accurate sensor placement for orthogonal three-axis sensing applications. |
| **Solid State** | This small device reduces board assembly costs, improves reliability and ruggedness compared to mechanical fluxgates. |
| **Low Power** | The patented on-chip set/reset and offset straps have been improved and now require 50% less power to drive the set-reset and offset functions. This sensor can be operated with a 3 to 25 volt power supply, lowering power consumption and reducing support circuitry. |
| **Cost Effective** | The sensors were specifically designed to be affordable for high volume OEM applications. |

## MR SENSOR CIRCUIT / PINOUT SPECIFICATIONS



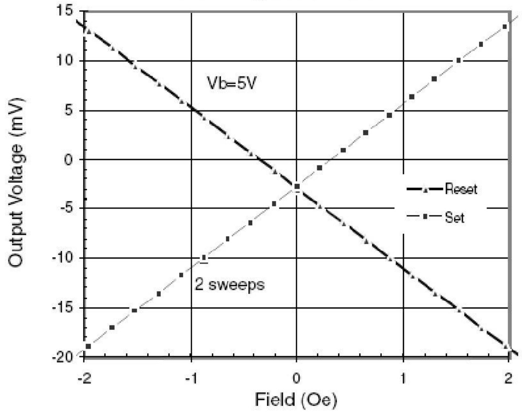



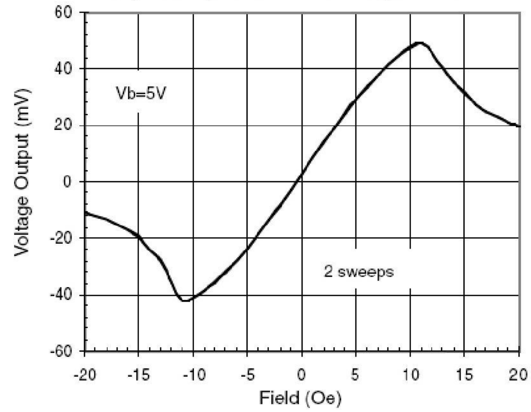

(millimeters)

## KEY PERFORMANCE DATA

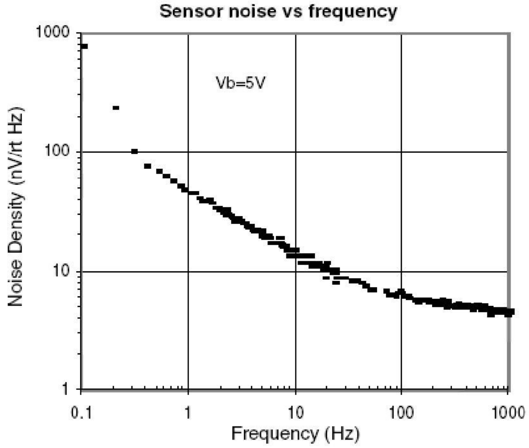
**Sensor output vs magnetic field after being set or reset**



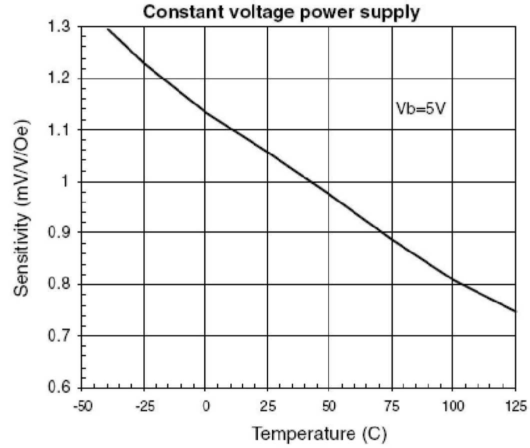

**Sensor output vs magnetic field Output is repeatable in field range ±20 Oe**



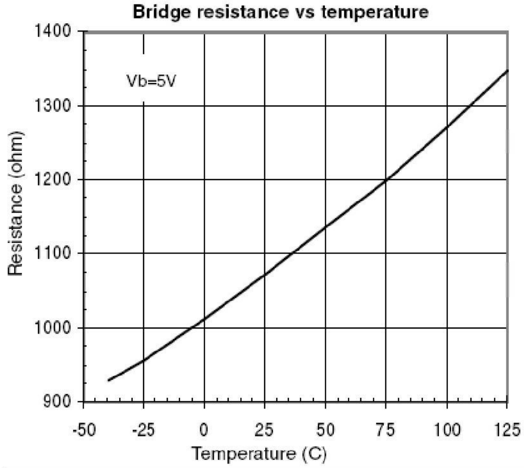

**Sensor noise vs frequency**



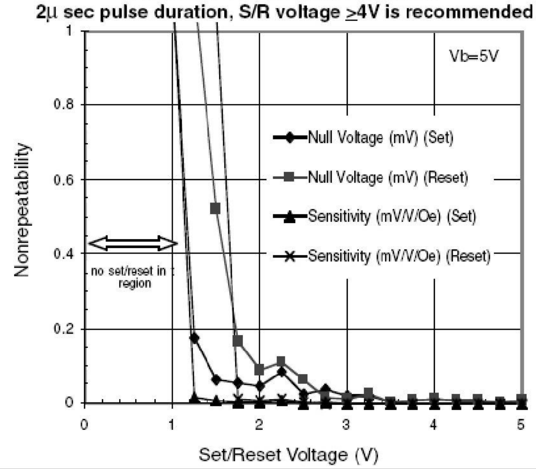

**Sensitivity vs temperature Constant voltage power supply**




**Bridge resistance vs temperature**




**Effects of set/reset pulse variation 2μ sec pulse duration, S/R voltage ≥4V is recommended**



## SPECIFICATIONS

| Characteristic | Conditions | Min | Typ | Max | Unit |
|---|---|---|---|---|---|
| Bridge Supply | Vbridge referenced to GND | 3 | 5 | 12 | Volts |
| Bridge Resistance | Bridge current = 5mA | 250 | 350 | 450 | Ω |
| Operating Temperature | Ambient | -40 | | 125 | ° C |
| Storage Temperature | Ambient, unbiased | -55 | | 125 | ° C |
| Field Range | Full scale (FS) — total applied field | -6 | | +6 | gauss |
| Linearity Error | Best fit straight line (at 25° C) ±1 gauss<br>±3 gauss<br>±6 gauss | | 0.05<br>0.4<br>1.6 | | %FS |
| Three-Axis Orthogonality | Angle from 90° | | ±1 | | degrees |
| Hysteresis Error | 3 sweeps across ±3 gauss @ 25° C | | 0.08 | | %FS |
| Repeatability Error | 3 sweeps across ±3 gauss @ 25° C | | 0.08 | | %FS |
| Bridge Offset | Offset = (OUT+) - (OUT-), Field=0 gauss after Set pulse, Vbridge=5V | -10 | ±2.5 | +10 | mV |
| Sensitivity | At Vbridge=5V | 0.8 | 1.0 | 1.2 | mV/V/gauss |
| Noise Density | Noise at 1Hz, Vbridge=5V | | 48 | | nV/√Hz |
| Resolution | Bandwidth=10Hz, Vbridge=5V | | 85 | | µgauss |
| Bandwidth | Magnetic signal (lower limit = DC) | | 5 | | MHz |
| OFFSET Strap | Measured from OFFSET+ to OFFSET- | 40 | 50 | 60 | Ω |
| OFFSET Strap ΩTempco | $T_A$=-40 to125° C | | 3900 | | ppm/° C |
| OFFSET Field | Field applied in sensitive direction | 4.0 | 4.6 | 6.0 | mA/gauss |
| Set/Reset Strap (1) | Measured from S/R+ to S/R- | 2.0 | 3.0 | 4.0 | Ω |
| Set/Reset Current (1) | 2µS current pulse | 1.5 | 2.0 | 4.0 | Amp |
| Disturbing Field | Sensitivity starts to degrade. Use S/R pulse to restore sensitivity. | 20 | | | gauss |
| Sensitivity Tempco | $T_A$=-40 to 125° C Vbridge=5V<br>Ibridge=5mA | -2800 | -3000<br>-600 | -3200 | ppm/° C |
| Bridge Offset Tempco | $T_A$=-40 to 125° C no Set/Reset<br>Ibridge=5mA with Set/Reset | | ±500<br>±10 | | ppm/° C |
| Resistance Tempco | Vbridge=5V, -40 to 125° C | | 2500 | | ppm/° C |
| Cross-Axis Effect | Cross field=1gauss (see AN-205) Happlied=±1 gauss | | +0.3 | | %FS |
| Max. Exposed Field | No perming effect on zero reading | | | 200 | gauss |

(1) Three in parallel.

Units: 1 gauss (G) = 1 Oersted (in air), 1G = 79.58 A/m,
1G = 10E-4 Tesla, 1G = 10E5 gamma

## Appendix F: VAS400 Ducted Fan Datasheet

# Ducted fan for motors 400 and 480

**Vasafan 65**

| | |
|---|---|
| Outside diameter | 66 mm |
| Inner diameter | 65 mm |
| Length | 75 mm |
| Weight without motor | 35 g |

**Vasafan 65G**

| | |
|---|---|
| Inner diameter | 65 mm |
| Max. diameter | 80 mm |
| Length | 110 mm |
| Weight without motor | 50 g |

It is possible to use ducted fan unit from carbon for models with weight three times more than is static thrust of complete unit. Of course, lower weight of model is better for performance of your model. Optimal ratio between thrust and total weight is 1:2 to 1:2,5.
Use the Graupner Speed 400 6V, Speed 480, 200/20/... or most powerful brushless motor like Kontronik.

**Table of Fans**

| Cat. Nr. | Fan | Description |
|---|---|---|
| 01 | Vasafan 65/1 | For motors with outside dia Ø 29 mm, dia of axle 2,3mm |
| 02 | Vasafan 65/2 | For motors with outside dia Ø 29 mm, dia of axle 3,17mm |
| 03 | Vasafan 65/3 | For motors with outside dia Ø 30,5 mm, dia of axle 2,3mm |
| 04 | Vasafan 65/4 | For motors with outside dia Ø 30.5 mm, dia of axle 3,17mm |
| 14 | Vasafan 65/1G | For motors with outside dia Ø 29 mm, dia of axle 2,3mm |
| 15 | Vasafan 65/2G | For motors with outside dia Ø 29 mm, dia of axle 3,17mm |
| 16 | Vasafan 65/3G | For motors with outside dia Ø 30,5 mm, dia of axle 2,3mm |
| 17 | Vasafan 65/4G | For motors with outside dia Ø 30.5 mm, dia of axle 3,17mm |

**Table of performances**

| Motor | V | A | Thrust (g) |
|---|---|---|---|
| Speed 400 6V | 9,6 | 8,5 | 230 |
| | 10,2 | 9,5 | 250 |
| | 11,2 | 10,5 | 280 |
| | 11,6 | 11 | 300 |
| Jamara 480 Pro | 11,8 | 9,5 | 280 |
| Speed 480BB | 8,4 | 15 | 280 |
| | 9,6 | 16 | 305 |
| | 11,1 | 18 | 350 |
| VM- 2020/27 | 11,6 | 11,7 | 330 |
| | 12,0 | 12,8 | 350 |
| VM- 2014/27 | 7,2 | 14 | 250 |
| | 8,5 | 17 | 320 |
| | 9,5 | 20 | 384 |
| | 9,7 | 20,5 | 410 |
| | 10,7 | 24 | 475 |

**Motor and cells connection**

| Motor | Cells |
|---|---|
| Speed 400 6V | 10 x Sanyo 500 mAh |
| 2 x Speed 400 6V | 10 x Sanyo 1000 (1250) mAh (paralel) |
| Speed 480 | 10 x Sanyo 800 mAh |
| 2 x Speed 480 | 10 x Sanyo 1700mAh (paralel) |

## Appendix G:  Team Members' Vitae